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Title of Research: **GRO: Red-Shifted Electron-Positron Annihilation Gamma-Rays from Radiopulsars**

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Reported red-shifted $e^+ + e^- \rightarrow \gamma + \gamma$ 511 keV γ-rays from the Crab pulsar would, if ultimately confirmed, provide crucial clues about the structure of the powerful magnetospheric accelerator in that rapidly spinning γ-ray pulsar. In attempting to understand the origin of this component of the Crab pulsar's emission we (T. Zhu and M.R.) must account for

1) a flow of $\sim 10^{40} e^{\pm} \mathrm{s}^{-1}$ into near the surface of the neutron star (Fig. 1),
2) a relatively narrow annihilation line implying that the annihilating $e^{\pm}$ pairs probably had a velocity (along $\vec{B}$) $\lesssim 10^{-1} c$ (Fig. 1),
3) a tentative light curve suggesting a doubly peaked structure different from that of the rest of the Crab pulsar's non-thermal radiation (Fig. 2).

1. The required $\dot{N}_{\pm} \sim 10^{40} \mathrm{s}^{-1}$ appears much too great to be accounted for in polar cap accelerator models. The absolute minimum required power, $2\dot{N}_{\pm} mc^2 \sim 2 \cdot 10^{34} \mathrm{erg\ s}^{-1}$, already reaches the maximum total power which could be generated by a polar cap accelerator ($\Omega^2 B_s R^3/ec \times 10^{12} eV \sim 2 \cdot 10^{34} \mathrm{erg\ s}^{-1}$) and it is difficult to see how the needed $e^{\pm}$ pair production can be accomplished with near 100% efficiency. Typically in polar cap accelerator models each $e^{\pm}$ pair is created by the materialtization of a $\gtrsim 10^2$MeV "curvature" emitted γ-ray crossing the strong local megnetic field so that at least $10^{36} \mathrm{erg\ s}^{-1}$ would be needed to account for the required $e^{\pm}$ production rate. Further, we were also unable to understand how the *outward* $e^{\pm}$ flow on the open field bundle through a polar cap accelerator could be reversed to become an *inward* directed flow. Any $e^{\pm}$ shower production directed toward the polar cap from the accelerator itself would deposit its energy so far below the polar cap surface that narrow $e^{\pm}$ annihilation line emission from that surface would be negligible relative to the resulting X-ray emission. We have, therefore, looked at outer-magnetosphere accelerators as the possible source of $\dot{N}_{\pm}$ since these, quite generally, can mobilize a much greater fraction of a nuetron star's spin-down power than that in

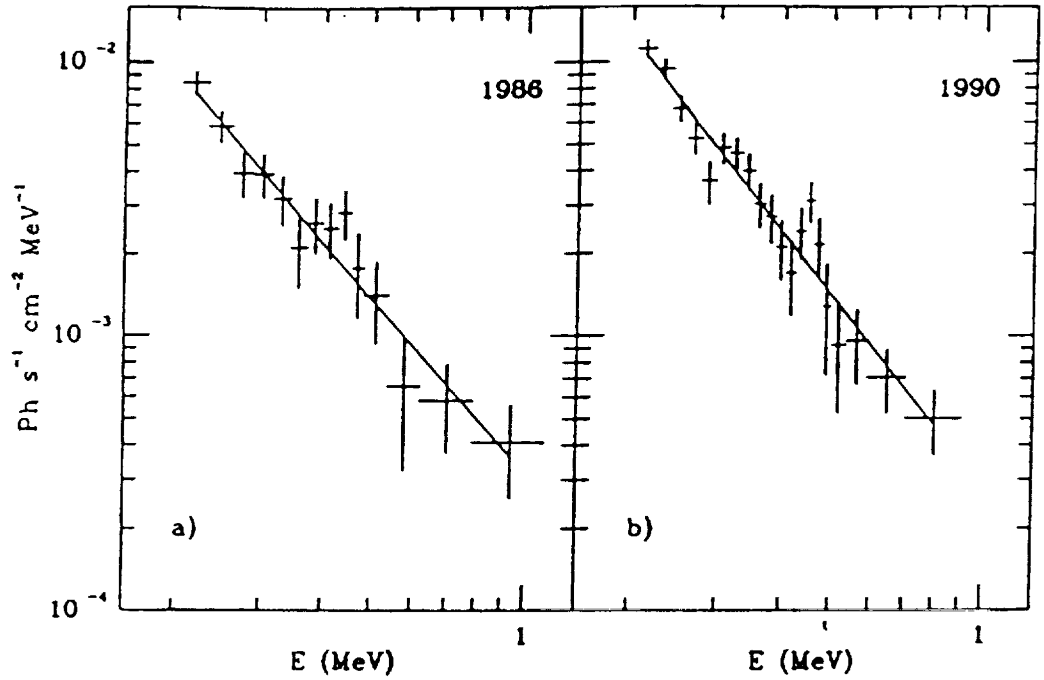

Fig. 1. The net spectra of the Crab photons after subtraction of the off-pulse signal, for the two FIGARO II flights of (a) 1986 July 11 and (b) 1990 July 9.

a polar-cap accelerator. (For the recently identified γ-ray pulsar PSR 1055–52 the high ratio of γ-ray luminosity to spin-down power seems to admit no other possible accelerator location.) That such accelerators are indeed the source of Crab pulsar γ-rays has long been argued because that pulsar's pulsed optical emission (coincident with its γ-ray emission) seems to be synchrotron radiation. An efficient source of such low energy synchrotron emission must be in a region of relatively weak magnetic field ($B \lesssim 10^8 G$) found only far ($r \gtrsim 4 \cdot 10^7$cm) from the stellar surface. The observed Crab pulsar optical luminosity – and, indeed all of its radiation below $\sim$ 1MeV – can be understood as a consequence of an $\dot{N}_{\pm} \sim 10^{39} - 10^{40}\mathrm{s}^{-1}$ outer-megnetosphere production rate. $\dot{N}_{\pm}$ depends on the local magnetic field ($10^8 G - 10^6 G$) which is sensitive to the exact location of the radiating pairs. Finally, the outer-magnetosphere accelerator models, unlike polar cap ones, give very similar $\dot{N}_{\pm}$ flowing down toward the polar caps and flowing out into the pulsar wind which ultimately powers the Crab Nebula emission. Here again an $\dot{N}_{\pm} \sim 10^{38} - 10^{40}\mathrm{s}^{-1}$ seems quite compatible with observations.

In outer-magnetosphere accelerator models $e^{\pm}$ production is coupled to the observed

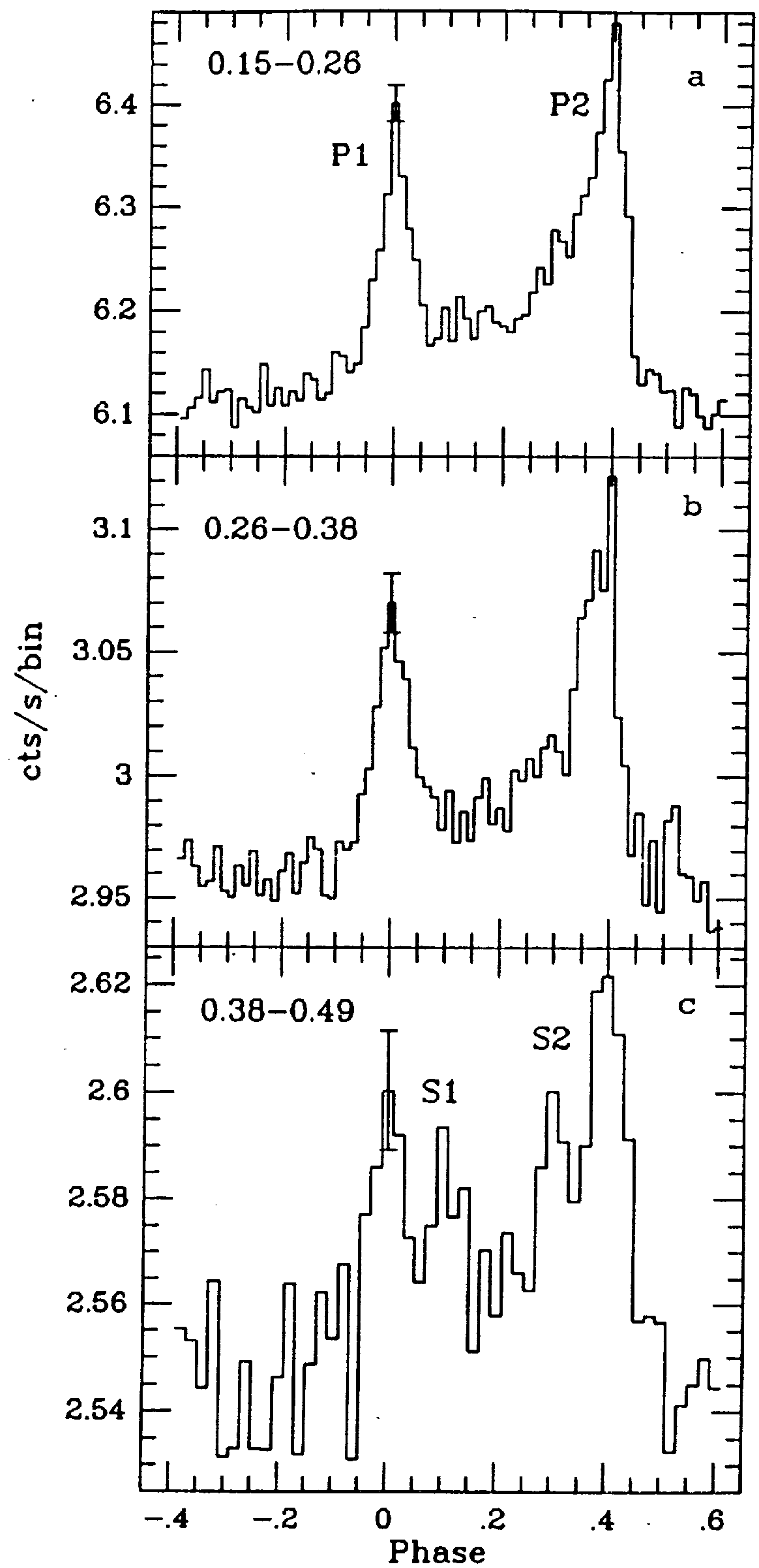

Fig. 2 a,b,c. Phase histograms of PSR 0531+21 in different energy bands. The zero phase corresponds to the main radio peak. The energy ranges (in MeV) are reported in each panel. From Massaro *et al.* 1992, preprint.

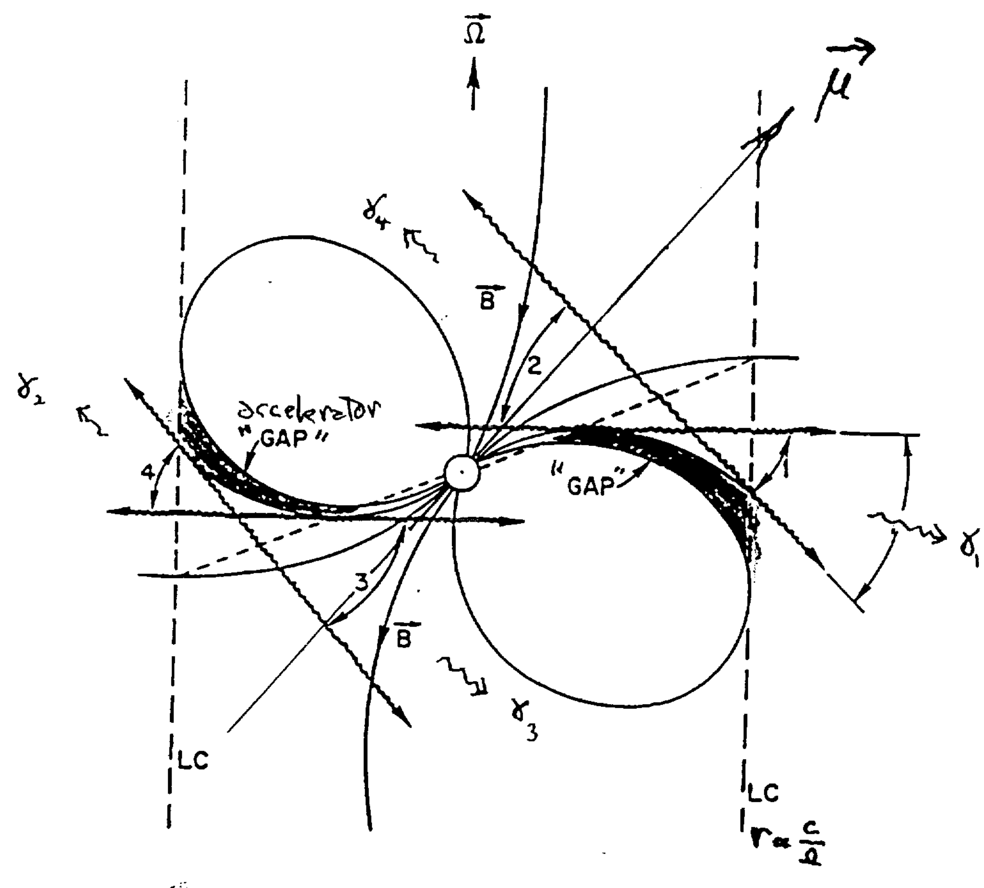

Fig. 3. Position of Crab pulsar outer-magnetosphere accelerators (dark areas) and four fan beams of emitted radiation from them.

Crab pulsar γ-rays and, presumably, with all of the other recently identified γ-rays from various other pulsars. We are, therefore, now attempting to extend outer-magnetosphere $e^{\pm}$ production models to all of the γ-ray pulsars. (All of these seem to have quite similar total γ-ray luminosity despite spin-down powers which vary over four orders of magnitude.)

The only pair production mechanism which we have found which seems efficient enough to give $\dot{N}_{\pm} \sim 10^{40}\mathrm{s}^{-1}$ in the Crab pulsar is that from outer-magnetosphere accelerator powered fan beam crossings which is characteristic of such models ($\gamma_1 + \gamma_2 \rightarrow e^+ + e^-$ and $\gamma_3 + \gamma_4 \rightarrow e^+ + e^-$ in Figure 3). This source geometry also gives comparable $e^{\pm}$ flows toward the two polar caps and also away from and toward the neutron star. The beam spectra and intensity of beams 1 and 3 (or 2 and 4) are to be associated with the observed Crab pulsar's pulse and interpulse. This model is comfortable with $\dot{N}_{\pm} \sim 10^{39}\mathrm{s}^{-1}$ but can achieve $\dot{N}_{\pm} \sim 10^{40}\mathrm{s}^{-1}$ with a somewhat uncomfortable stretching of expected accelerator parameters. Other ways of making $e^{\pm}$ pairs include the pair conversion of very high energy γ-rays ($E_\gamma >$ GeV) from the outer-magnetosphere accelerator by collisions with soft X-rays from the stellar surface (probably the dominant pair production mechanism in Geminga, Vela, PSR 1055-53, and PSR 1706). We do not find this mechanism to be as important as the crossed beam one of Fig. 3. for the Crab. We have also tried to predict the red-shifted pair annihilation line intensity in the other γ-ray pulsars assuming that the Crab pulsar and PSR 1509 have the stronger local fields at their outer-magnetosphere accelerators than Geminga, PSR 1055, 1706, and Vela which have different inclination angles between their spin axes and dipole moments but very similar accelerators (each about 10^8cm from the neutron stars. This is needed to maintain enough bootstrapped $e^{\pm}$ production within the accelerators to give powerful γ-ray sources with $L_\gamma \sim 4 \cdot 10^{34}$erg s^{-1}.) We have found the best candidate for an $\dot{N}_{\pm}$ annihilation line comparable to that from the Crab to be PSR 1509. However, when the inclination angle is large as in Geminga and PSR 1055, outer-magnetosphere produced γ-rays with an $E_\gamma >$ 1GeV may pass close enough to the neutron star for pair production by $\gamma + \vec{B} \rightarrow e^+ + e^- + \vec{B}$ to be significant. This can make the relatively close Geminga also a possible observable source for red-shifted $e^{\pm}$ annihilation γ-rays.

2. Essentially all $e^{\pm}$ relativistic motion perpedicular to $\vec{B}$ will be lost to synchrotron radiation long before inflowing $e^{\pm}$ get near the stellar surface. The residual motion along $\vec{B}$ has a $\vec{v}\cdot\hat{B} \sim 10^{10}$cms^{-1}. Because of increasing $e^{\pm}$ density as the polar cap is approached annihilation takes place somewhat above the surface. Resonant scattering of e^- and e^+ by soft X-rays from the Crab pulsar surface at those r where the photon frequency

$$\omega_B = \frac{eB}{mc}\left(\frac{R}{r}\right)^3$$

may keep $e^{\pm}$ from reaching the surface even if annihilation did not preempt it. It will certainly reduce $\vec{v}\cdot\hat{B}$ near the annihilation region. We are trying to include this effect on the Doppler shift addition to the gravitational red shift of the annihilation γ-rays. (Possible $e^{\pm}$ cyclotron-resonance-screens may also exist in Geminga, PSR 1055, and Vela, and play an important role in understanding the observed soft X-ray emission from their surfaces. We are, therefore, attempting to expand somewhat our study of $e^{\pm}$ production and annihilation in the Crab pulsar to some of these other γ-ray pulsars.)

3. In calculating the annihilation line energy (and profile) we must also include the effect of the time varying geometry in which part of the relevant region above the polar caps is often on the unobservable side of the star for part or all of a spin-cycle. The averaged gravitational red-shift seems not insensitive to whether the polar cap structure is sunspot-like (as seems the case for Geminga) or closer to that of the conventionally assumed central dipole. We have some toy model results but not yet definitive conclusions (except that understanding the claimed annihilation ling light curve seems difficult).